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PHYSIOLOGICAL RESPONSES TO VARYING WORKLOADS AND CONFIGURATIONS OF THE MCU-2/P CHEMICAL DEFENSE MASK

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The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-3.

The Office of Public Affairs has reviewed this paper, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

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13. ABSTRACT *(Maximum 200 words)*

An objective of this study was to evaluate the breathing resistance characteristics of MCU-2/P and M-17 chemical defense masks during individual exposures to 8 consecutive incremental workloads. Other objectives included: evaluation of cardiorespiratory and subjective responses and testing of two commercially available blowers. Five MCU-2/P mask configurations were tested: mask without filter (MCU-0F), mask + 1 filter (MCU-1F), mask + 2 filters (MCU-2F), mask + 1 filter + blower A (MCU-1F-ABA), and mask + blower B + 2 filters (MCU-ABB-2F). An M-17 mask was also tested. Each subject walked on a treadmill for 5 min at each of 8 consecutive incremental workloads (ranging from 26% to 77% of $VO_{2\,MAX}$) for a total of 40 min, while wearing each mask configuration. Variables measured included inspiratory and expiratory mask cavity pressures (IMCP & EMCP), mask cavity pressure-swing (MCPS), peak inspiratory airflow (PIAF), respiratory rate (RR), tidal volume (V_T), minute volume (VE), heart rate (HR), perceived inspiratory & expiratory effort (PIE & PEE), and overall breathing discomfort (OBD). The MCU-1F and M-17 masks imposed the same magnitudes of inspiratory resistance at any given workload. The highest inspiratory resistance was imposed by the MCU-1F and M-17 masks, while the lowest corresponded to the MCU-ABB-2F and MCU-2F. Either of these two masks can be expected to decrease individual tolerance to sustained physical work. The MCU-ABB-2F and the MCU-2F were the most effective methods to reduce the magnitude of inspiratory resistance at any given workload.

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PHYSIOLOGICAL RESPONSES TO VARYING WORKLOADS AND CONFIGURATIONS OF THE MCU-2/P CHEMICAL DEFENSE MASK

INTRODUCTION

Results from our previous studies have suggested that the MCU-2/P ground-crew chemical defense (CD) mask in its current operational configuration (1 filter) does not offer an improvement in reducing the magnitude of external breathing resistance when compared to the M-17 CD mask. These results have also suggested that a feasible approach to decrease the magnitude of external inspiratory resistance associated with the use of the MCU-2/P CD mask is to provide assisted ventilation through the C2 filter canister. The use of a "Pusher Blower" (Racal Health & Safety), which was designed specifically to be used in conjunction with the C2 filter canister, proved to be effective in reducing the magnitude of external inspiratory resistance observed among subjects exposed to sustained exercise of moderate intensity (about 37% of $Vo_{2\,MAX}$). However, additional manikin tests provided some evidence that this blower could have difficulties handling higher inspiratory air flows associated with intense physical exercise; and, consequently, it could become an additional source of external inspiratory resistance under these conditions.

The objectives of this study were: 1) investigate the magnitude of external breathing resistance imposed by the MCU-2/P (5 configurations) and the M-17 CD masks during physical exercise of various intensities, 2) determine the effects of these exposures on several individual cardiorespiratory variables and subjective responses, 3) evaluate the effectiveness of two commercially available blowers to reduce the magnitude of external inspiratory resistance imposed by the MCU-2/P CD mask under these conditions, and 4) elaborate recommendations concerning methods to reduce the external inspiratory resistance associated with this mask.

METHODS AND MATERIALS

Five MCU-2/P mask configurations were tested (Figs. 1a - 1e): 1) mask without a filter (MCU-0F), 2) mask with 1 filter canister (MCU-1F), 3) mask with 2 filters (MCU-2F), one on each side of the mask, 4) mask with 1 filter and a powered blower ("A") attached to the inlet opening of the filter (MCU-1F-ABA), and 5) mask with a powered blower ("B") connected to the inlet valve assembly of the mask, and with 2 filters attached to the inlets of the blower unit (MCU-ABB-2F). The voicemitter on the right side of the facepiece of the MCU-2/P mask was replaced with an inlet valve assembly in order to accommodate a second filter canister (MCU-2F). Two different types of air blowers were used to provide assisted ventilation to the subjects. "ABA" (Pusher Blower - manufactured by Racal Health & Safety, Inc.) was a continuous-flow unit that supplied an average flow rate (during inspiration) of 80 $L \cdot min^{-1}$ (2.8 cfm) of ambient air

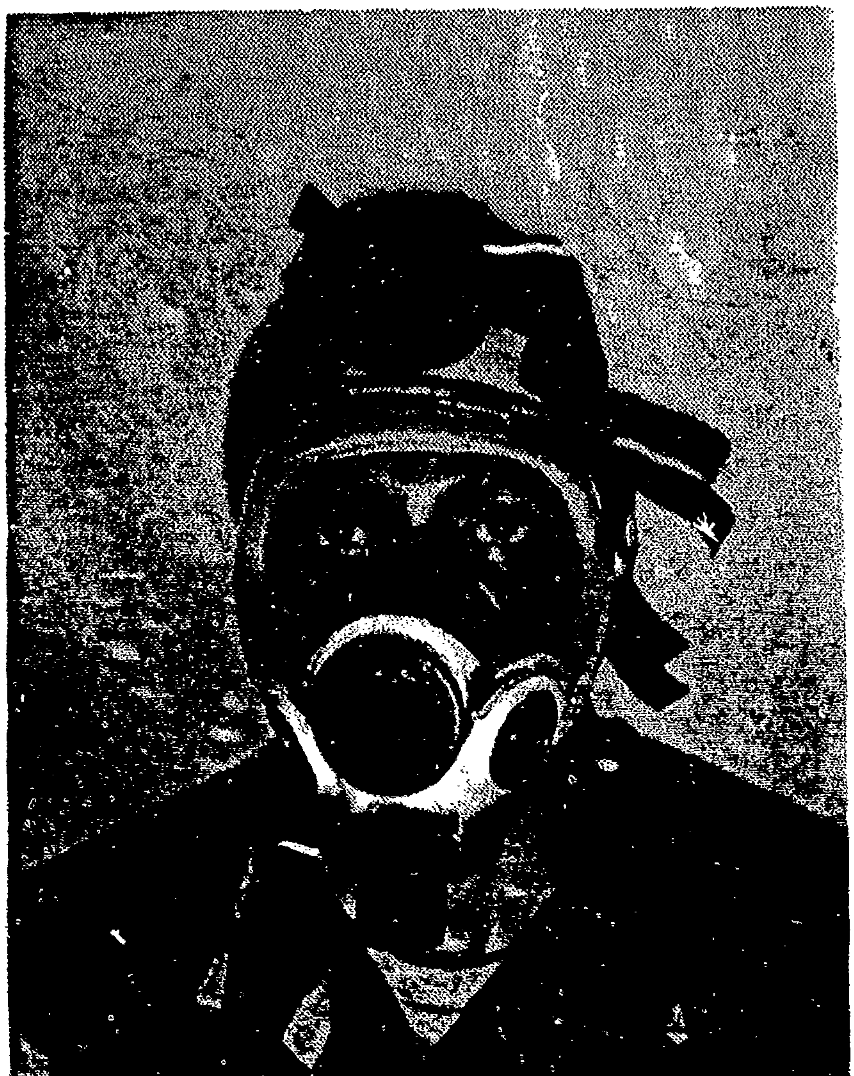

Figure 1a. MCU-2/P without filter (MCU-0F).

Figure 1b. MCU-2/P with 1 filter canister (MCU-1F).

Figure 1c. MCU-2/P with 2 filters (MCU-2F).

Figure 1d. MCU-2/P with 1 filter and air blower A (MCU-1F-ABA).

Figure 1e. MCU-2/P with air blower B and 2 filters (MCU-ABB-2F).

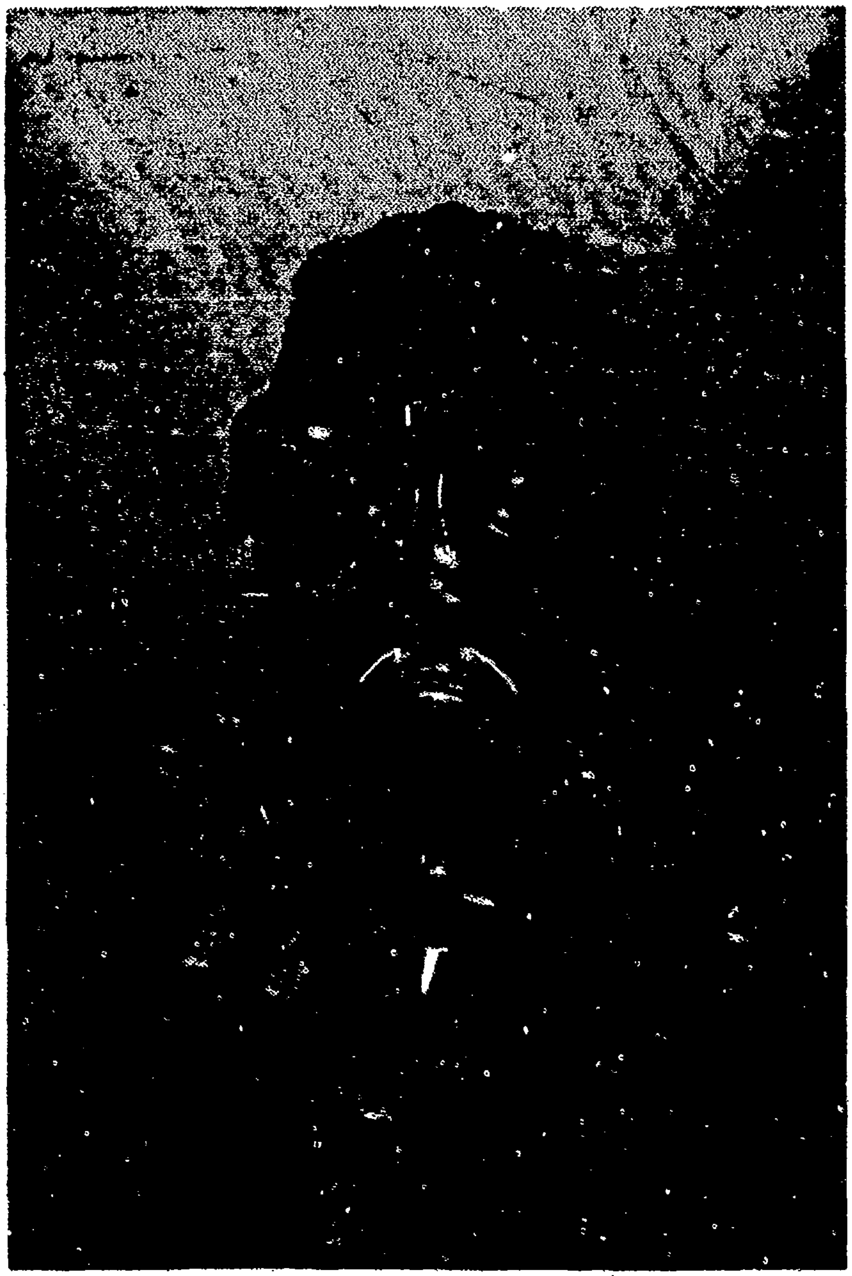

Figure 1f. M-17 mask.

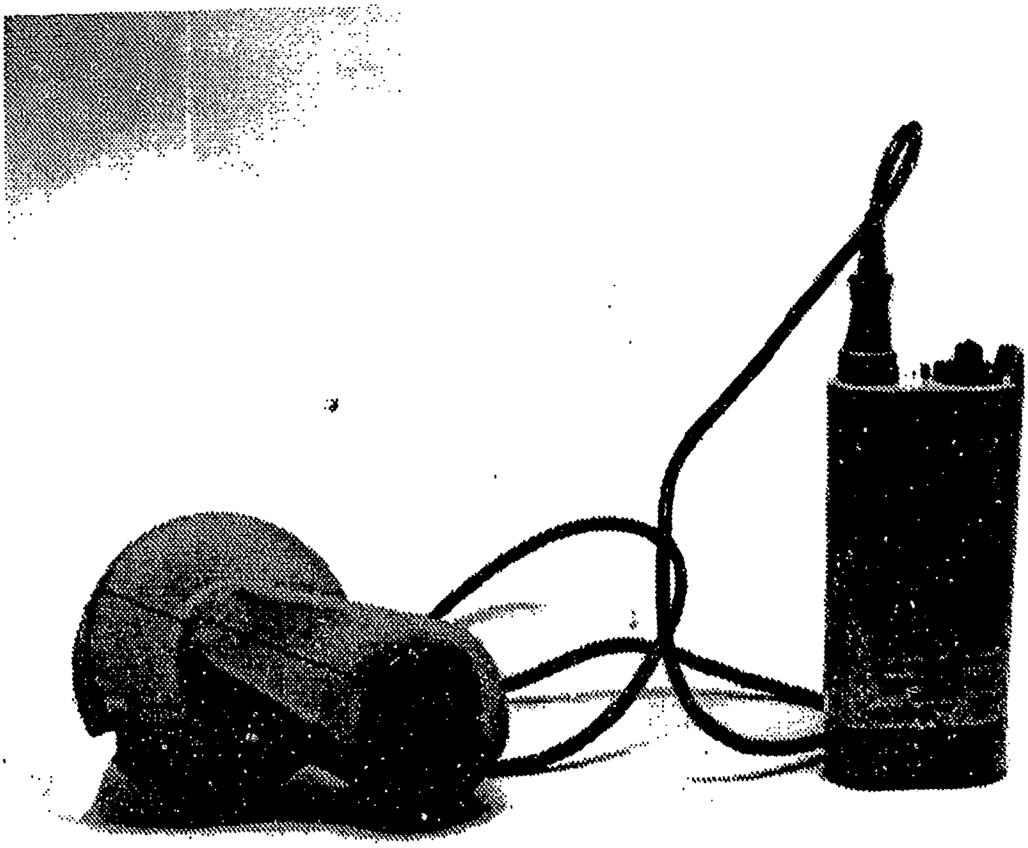

Figure 1g. Air Blower A (Pusher Blower - Racal Health & Safety).

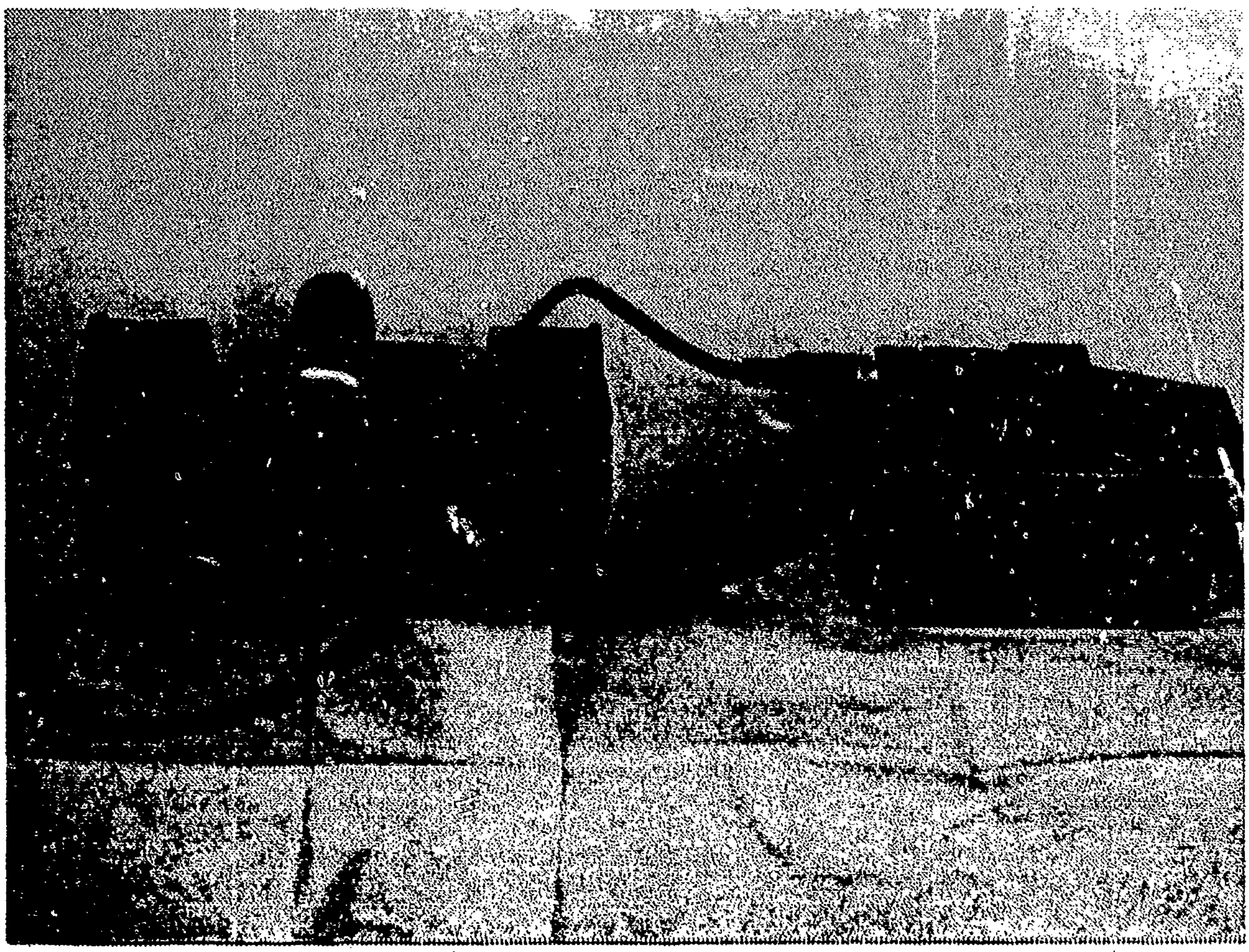

Figure 1h. Air Blower B (T8N Fan-Motor Unit - KASCO).

through the C2 filter canister. "ABB" (T8N Fan-Motor Unit - manufactured by KASCO-cermac) was also a continuous-flow unit that supplied an average flow rate (during inspiration) of 70 $L \cdot min^{-1}$ (2.5 cfm) of filtered air through the inlet valve assembly. A rechargeable Nickel-Cadmium battery pack was used to operate ABA. A rechargeable Lead battery pack was used to operate ABB. A standard M-17 CD mask (Fig. 1f) was also included in this study in order to assess any differences in the breathing resistance characteristics of the MCU-2/P mask in its current operational configuration (with a single C2 filter canister).

Eight healthy male subjects were informed of the purposes and possible risks of this study, and signed informed consent statements in accordance with AFR 169-3. Each subject underwent a complete medical examination, pulmonary function testing, echocardiographic evaluation, and a progressive treadmill test. The physical characteristics of the subjects were (mean ± SD): age 32 ± 7.6 years; weight 79.25 ± 8.35 kg; height 177 ± 7 cm; $VO_{2\,MAX}$ 50.04 ± 4.6 $ml \cdot kg^{-1}$; VE_{MAX} 136 ± 8.4 $L \cdot min^{-1}$. Subjects wore shorts, tee-shirt, socks, tennis shoes, and were tested in a comfortable environment. They were instructed to avoid strenuous physical exercise on the testing days and not to modify their daily exercise habits throughout the duration of the study.

Table 1 describes the 8 different treadmill settings (speed and grade) used in our experiments, and the corresponding metabolic rates and ventilatory minute volumes measured among the subjects under each workload. This table also shows the mean relative workloads calculated from metabolic rate as a percentage of measured $VO_{2\,MAX}$, and the mean relative VEs calculated from minute ventilation as a percentage of measured VE_{MAX}. All of these baseline determinations did not include the testing of any of the 6 mask configurations used during the actual experiments. Therefore, it is reasonable to expect that the metabolic cost of exercising at each workload while wearing each of the CD masks should be higher. For the purpose of facilitating the description and discussion of the results we decided to classify the 8 workloads into 3 subgroups: Low (workloads 1, 2, 3), Moderate (workloads 4, 5), and High (workloads 6, 7, 8).

The physical task consisted of walking on a treadmill for 5 min at each of the 8 consecutive incremental workloads (Table 1), for a total 40 minutes per experiment. Each mask configuration was tested by each of the 8 subjects in a semi-randomized (counterbalanced) order. Subjects were tested once every other week in order to avoid carry-over (training) effects.

The variables measured during the experiments included: Inspiratory Mask Cavity Pressure (IMCP), Expiratory Mask Cavity Pressure (EMCP), Mask Cavity Pressure-Swing (MCPS), Peak Inspiratory Airflow (PIAF), Respiratory Rate (RR), Tidal Volume (V_T), Ventilatory Minute Volume (V_E), Heart Rate (HR), Perceived Inspiratory Effort (PIE), Perceived Expiratory Effort (PEE), and Overall Breathing Discomfort (OBD). Mask cavity pressures (IMCP & EMCP) were used as indicators of external resistance to breathing (inspiratory and expiratory). Mask Cavity Pressure-Swing (MCPS) was calculated by adding IMCP and EMCP values to determine a single

TABLE 1. PHYSICAL WORKLOADS USED FOR THE HUMAN TESTING OF THE MCU-2/P AND M-17 CD MASKS

	Treadmill Speed (mph)	Treadmill Grade (%)	Metabolic Rate * ($LO_2 \cdot min^{-1}$)	Metabolic Rate * (Watts)	Relative Load * (% of $Vo_{2\,MAX}$)	Minute * Ventilation ($L \cdot min^{-1}$)	Relative V_E * (% of $V_{E\,MAX}$)
1	3.0	0.5	1.02 ± .04	356 ± 15	26.0 ± 1.4	24.3 ± 1.6	18.0 ± 1.3
2	3.0	2.5	1.11 ± .04	387 ± 14	28.3 ± 1.4	26.3 ± 1.7	19.4 ± 1.4
3	3.0	5.0	1.33 ± .04	463 ± 15	33.8 ± 1.4	31.1 ± 1.7	23.0 ± 1.4
4	3.0	7.5	1.65 ± .05	574 ± 17	41.9 ± 1.5	38.8 ± 1.2	28.6 ± 1.1
5	3.0	10.0	1.98 ± .07	691 ± 24	50.4 ± 1.8	48.2 ± 2.3	35.6 ± 1.9
6	3.0	12.5	2.37 ± .08	826 ± 27	60.2 ± 2.1	59.5 ± 2.9	43.8 ± 2.2
7	3.0	15.0	2.71 ± .09	945 ± 30	68.9 ± 2.4	70.9 ± 3.5	52.1 ± 2.4
8	3.0	17.5	3.03 ± .10	1058 ± 33	77.1 ± 2.5	85.5 ± 3.4	62.8 ± 2.2

(*) Values are means ± SE

value that represented the total external resistance to breathing (inspiratory + expiratory) imposed by each of the 6 mask configurations. Group means were calculated for each variable and analyzed among the 6 different mask configurations for each of the 8 workloads using a repeated measures three-way analysis of variance (ANOVA) (subject as the random factor and mask configuration and workload as the fixed factors). A follow-up analysis was performed using a repeated measures two-way ANOVA (subject as the random factor and mask configuration as the fixed factor) in order to determine significant mask differences in each variable at any given workload. Whenever significant F values were found with the two-way ANOVA, a Duncan's Multiple Range Test was used to identify the specific differences between the various mask configurations. Results are presented in Figures 2-13 as group means.

Baseline metabolic rates (oxygen uptakes) and ventilatory minute volumes were determined for each subject using a SensorMedics Metabolic Measurement Cart (Model 2900). IMCP and EMCP were measured using a Validyne Pressure Transducer (Model DP15-50) and a Validyne Sine Wave Carrier Demodulator (Model CD15). PIAF was measured using a Fleisch Pneumotachograph connected to a Validyne Pressure Transducer (Model MP45-1) and a Validyne Sine Wave Carrier Demodulator (Model CD12). Ventilatory minute volumes were determined using a SensorMedics Ventilation Measurement Module (Model VMM-1). RR was obtained indirectly from the processing of the VMM-1 signal. A telemetry system (Transkinetics) was used to monitor HR and rhythm. All of these variables were continuously monitored and automatically recorded using a Lab View Data Acquisition System and a Macintosh FX Computer. Numerical scales were used to determine the level of both PIE and PEE. These scales ranged from 1 to 7, which represented a spectrum of breathing sensations ranging from "No Noticeable Effort" to "Intolerable Effort" (Appendix). Another numerical scale was used to evaluate OBD. This scale ranged from 1 to 7, to indicate sensations ranging from "No Discomfort" to "Intolerable Discomfort" (Appendix). PIE, PEE and OBD were manually recorded once under each workload.

RESULTS

Figure 2 shows the IMCPs measured at the mouth level inside the MCU-2/P (5 configurations) and M-17 masks while exercising at 8 incremental workloads. As expected, each mask configuration showed a progressive increase in IMCP during exposure to incremental workloads. The MCU-1F and M-17 masks produced the highest IMCPs when compared to any of the other mask configurations at any given workload. However, there were no significant differences in IMCP between them. The use of a second filter canister (MCU-2F) resulted in a significant reduction in IMCP compared to the MCU-1F at any given workload. The MCU-1F-ABA and MCU-ABB-2F showed the lowest IMCPs at the low workloads 1, 2, and 3. On the other hand, at high workloads 7 and 8, the MCU-0F (control) produced the lowest IMCPs. At moderate workload 4, the MCU-ABB-2F produced an IMCP similar to the MCU-0F (control); however, the IMCP in the MCU-1F-ABA was still significantly lower. At moderate workload 5 there were no significant differences in IMCP between MCU-0F, MCU-1F-ABA, and MCU-ABB-2F; nevertheless, they were lower compared to MCU-2F. At high workload 6, there were no significant differences in IMCP between MCU-1F-ABA, MCU-ABB-2F, and MCU-2F. At high workload 7, MCU-1F-ABA and MCU-ABB-2F showed no difference in IMCP compared to the MCU-2F, but were different when compared with each other. At high workload 8 there were no significant differences in IMCP between MCU-1F, M-17, and MCU-1F-ABA, nor between the MCU-2F and MCU-ABB-2F.

Figure 3 shows the EMCPs measured at the mouth level inside the MCU-2/P (5 configurations) and M-17 masks while exercising at 8 incremental workloads. All of the mask configurations showed a progressive increase in EMCP in response to incremental workloads. Results indicated that the MCU-1F-ABA produced the highest EMCPs at low workloads 1, 2, and 3 and at moderate workload 4. At moderate workload 5, there were no significant differences among any of the mask configurations. At high workloads 6, 7, and 8, the M-17 showed the highest EMCP, while the MCU-ABB-2F showed the lowest. There were other statistically significant differences in EMCP between mask configurations; however, the physiological implications of these differences are negligible.

Figure 4 shows the MCPSs calculated from IMCPs and EMCPs. As expected, MCPSs showed an overall response pattern very similar to that previously described for IMCP.

Figure 5 shows the PIAFs measured during the testing of MCU-2/P (5 configurations) and M-17 masks while exercising at 8 incremental workloads. Each mask configuration showed a progressive increase in PIAF in response to the incremental workloads. At the low workloads 1, 2, and 3, the MCU-1F-ABA produced a higher PIAF than the MCU-1F and M-17 masks. At moderate workload 4, there were no significant differences in PIAF among any of the mask configurations. At the high workloads 6, 7, and 8, the MCU-0F (control) and MCU-2F showed the highest PIAF, while the MCU-1F-ABA, MCU-1F, and M-17 showed the lowest PIAFs.

Figure 6 shows a plot of IMCPs vs. PIAFs. It can be observed that the IMCPs produced by the MCU-1F and the M-17 masks are almost identical at any given PIAF. At PIAFs between 70 and 95 $L \cdot min^{-1}$ the MCU-1F-ABA and MCU-ABB-2F maintained very low IMCPs (< .07 inH_2O). At a PIAF of about 105 $L \cdot min^{-1}$ the MCU-1F-ABA, MCU-ABB-2F, and MCU-0F (control) show the same IMCP. At a PIAF of about 145 $L \cdot min^{-1}$ the MCU-1F-ABA showed a higher IMCP compared to the MCU-2F. Furthermore, at a PIAF of about 170 $L \cdot min^{-1}$ there were no significant differences in IMCP between the MCU-1F-ABA, MCU-1F, and M-17 masks. At PIAFs between 130 and 200 $L \cdot min^{-1}$ there were no differences in IMCP among the MCU-2F and the MCU-ABB-2F.

Figure 7 shows the RRs recorded among the subjects during the testing of MCU-2/P (5 configurations) and M-17 masks at 8 incremental workloads. Each mask configuration showed a progressive increase in RR associated with a progressive increase in workload. At low workload 3 and high workloads 7 and 8, there were no

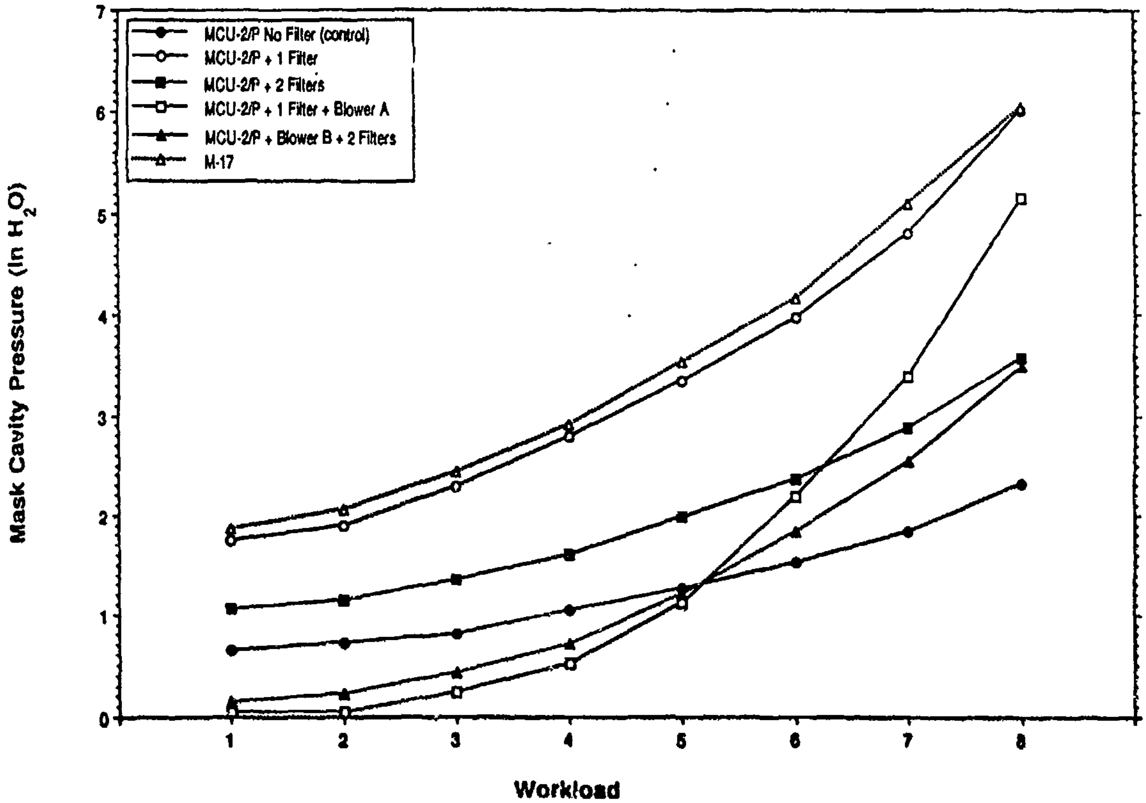

Figure 2. Inspiratory mask cavity pressure (MCP) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

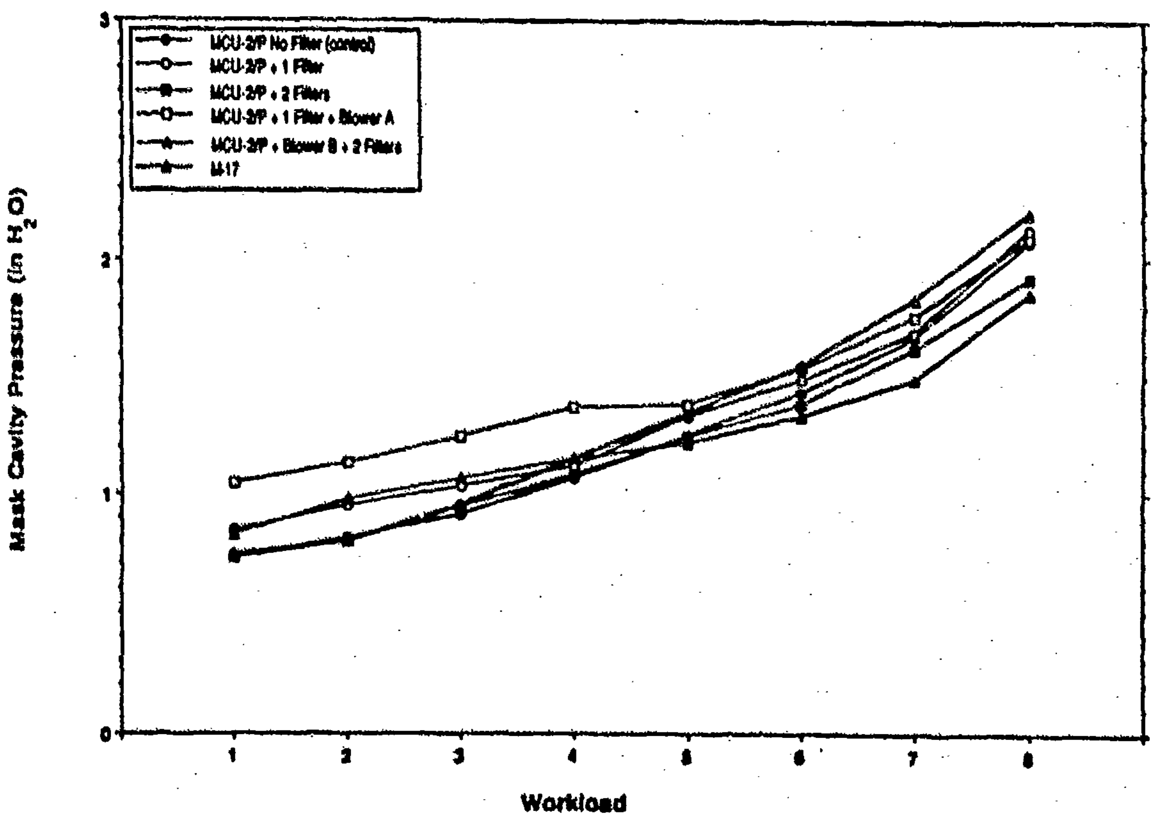

Figure 3. Expiratory mask cavity pressure (EMCP) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

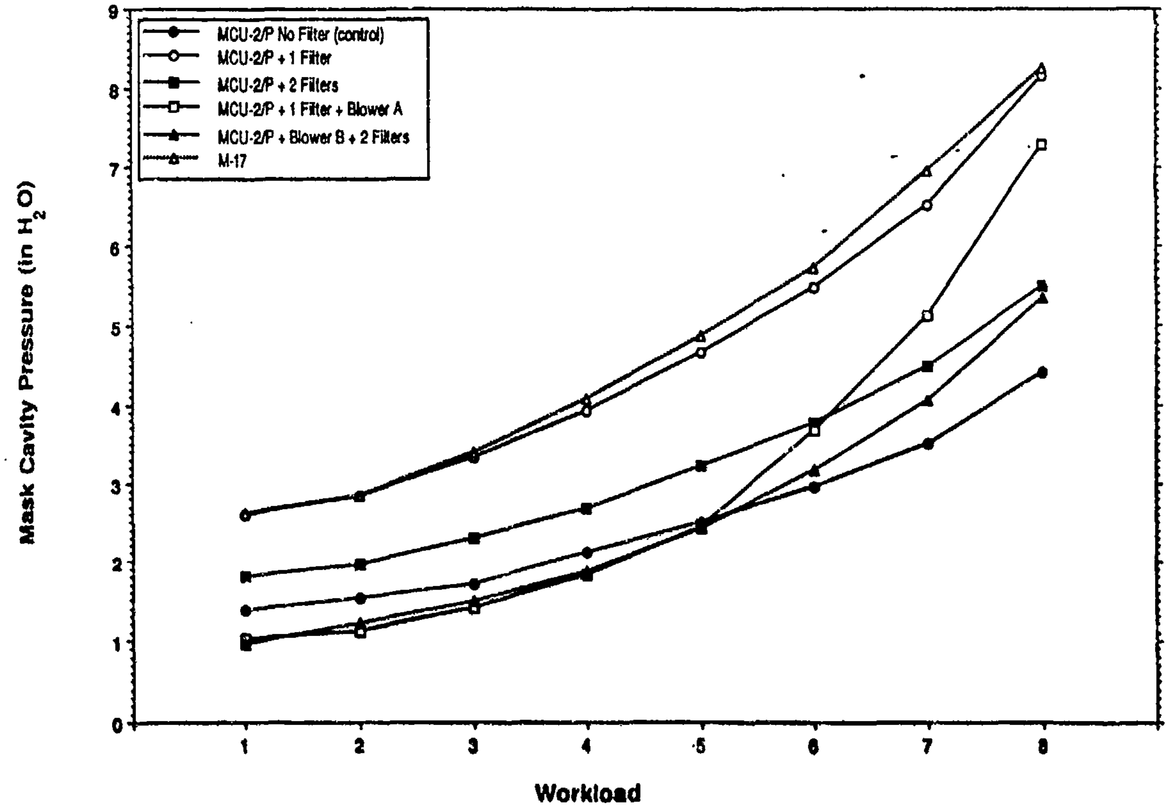

Figure 4. Mask cavity pressure-swing (MCPS) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

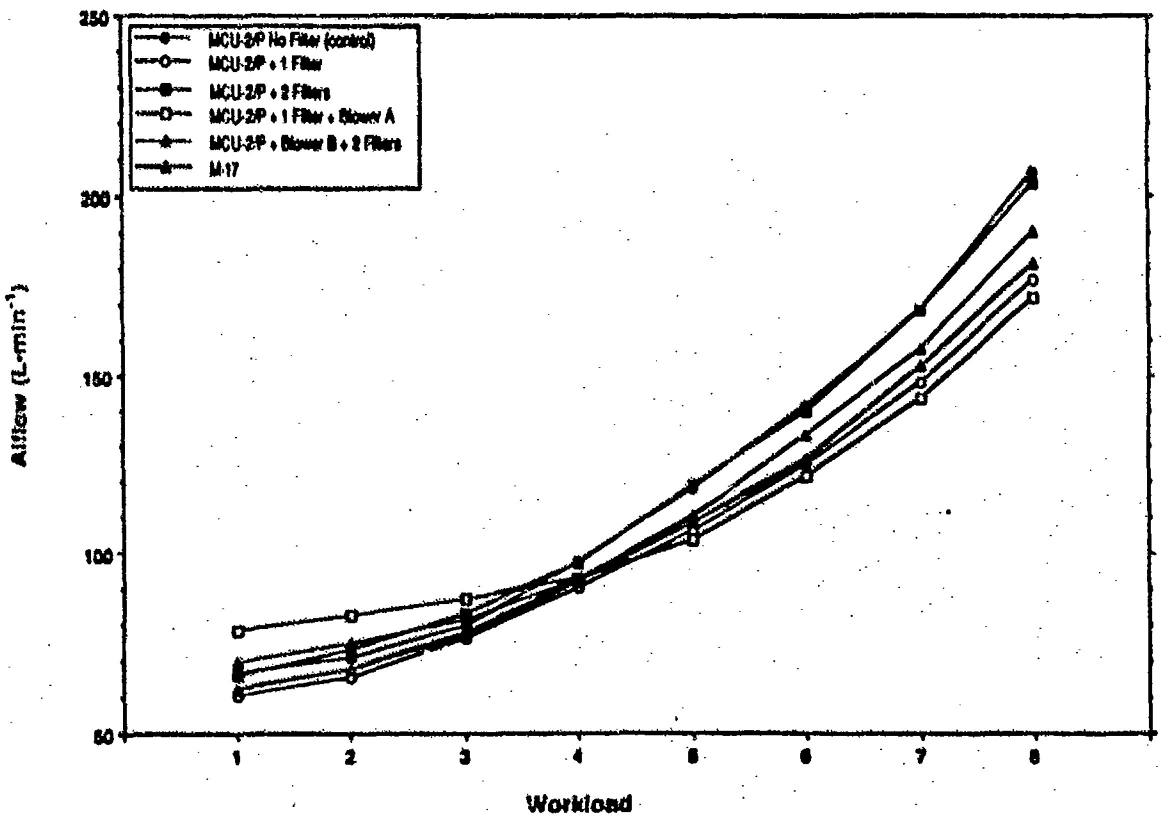

Figure 5. Peak inspiratory airflow (PIAF) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

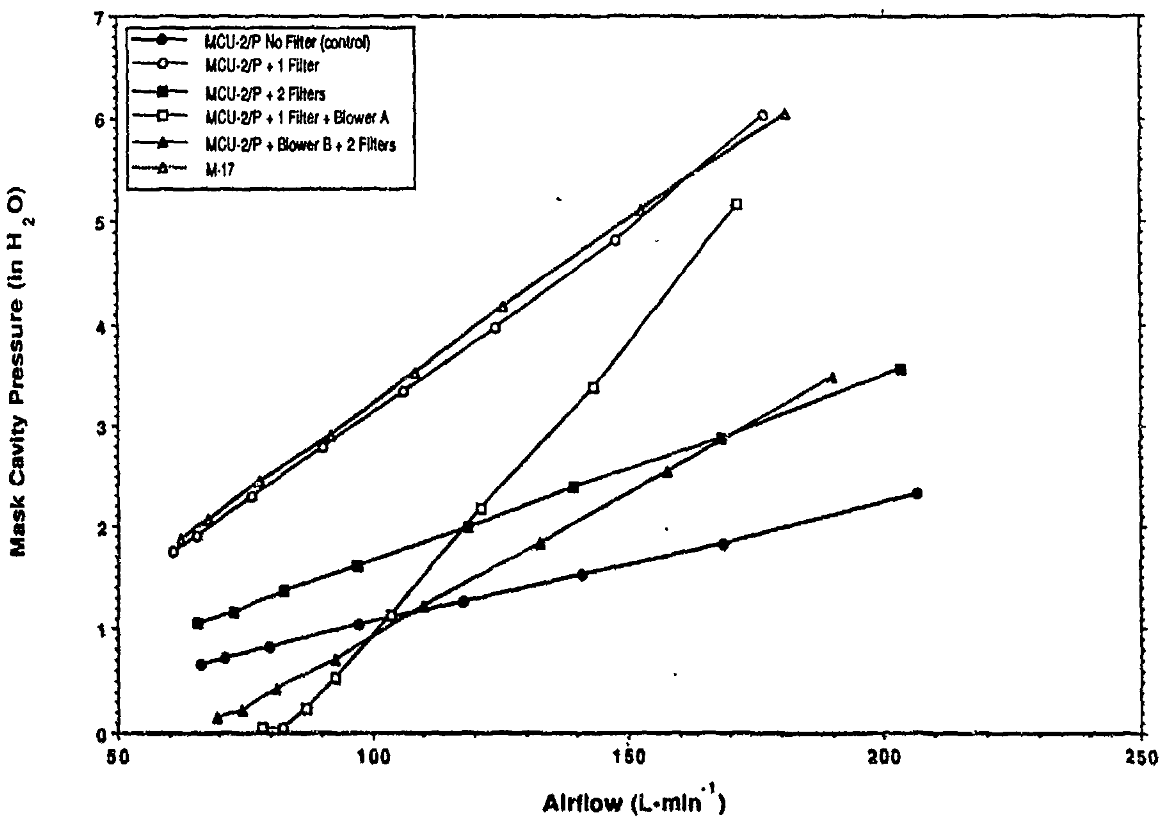

Figure 6. Inspiratory mask cavity pressure (MCP) as a function of peak inspiratory airflow (PIAF) during physical exercise wearing MCU-2/P (5 configurations) and M-17 CD masks.

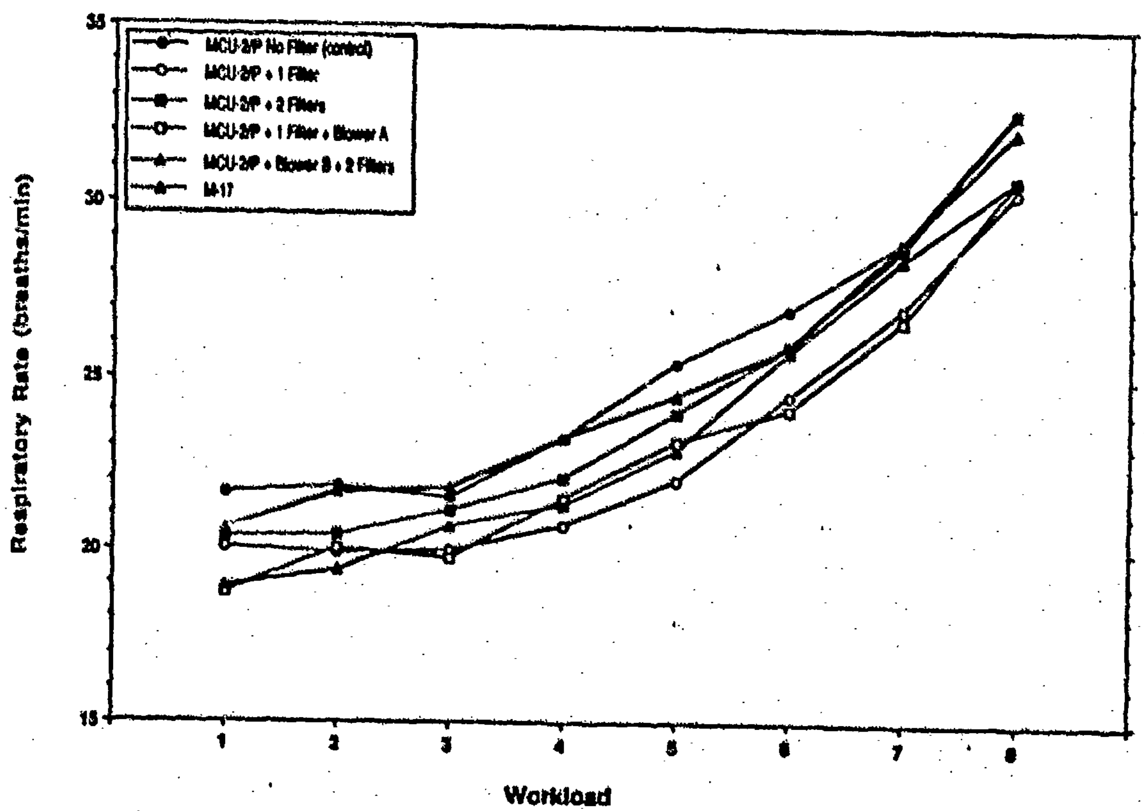

Figure 7. Respiratory rates (RR) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

significant differences in RR between any of the mask configurations. Although there were several significant differences in RR between mask configurations, the physiological relevance of these statistical differences is negligible.

Figure 8 shows the V_Ts recorded among the subjects during the testing of MCU-2/P (5 configurations) and M-17 masks at 8 incremental workloads. As expected, MCU-1F-ABA produced the highest V_Ts recorded at any given workload. MCU-ABB-2F produced the second highest V_Ts at any given workload. MCU-1F-ABA showed an overall trend towards a reduction of V_T in response to a progressive increase in workload. On the other hand, MCU-ABB-2F showed relatively constant V_T responses throughout the full range of workloads. At high workload 8, the MCU-ABB-2F showed no difference in V_T compared to the MCU-0F (control). The MCU-0F, MCU-1F, MCU-2F and M-17 masks showed a progressive increase in V_T in response to exposure to incremental workloads. At any given workload, the MCU-1F showed a significantly higher V_T compared to the M-17, whereas the MCU-0F (control) and MCU-2F showed no significant differences between each other.

Figure 9 shows the V_Es recorded among the subjects during the testing of MCU-2/P (5 configurations) and M-17 masks at 8 incremental workloads. All of the mask configurations showed a progressive increase in V_Es in response to incremental workloads. The MCU-1F-ABA showed the highest V_Es recorded at any given workload. MCU-ABB-2F showed the second highest V_Es except under high workload 8, where it was similar to the MCU-0F (control), MCU-2F, and MCU-1F. There were no significant differences in V_E between MCU-0F (control), MCU-1F, MCU-2F, and M-17 at the low workload 3, moderate workloads 4 and 5, and high workload 7. The M-17 mask showed the lowest V_Es at low workloads 1 and 2, and high workloads 6 and 8. At the high workloads 6 and 8, the M-17 showed a significantly lower V_E compared to the MCU-0F (control), while the MCU-1F and MCU-2F showed no differences between each other.

Figure 10 shows the HRs recorded among the subjects during the testing of MCU-2/P (5 configurations) and M-17 masks at 8 incremental workloads. All of the mask configurations showed a progressive increase in HR in response to incremental workloads. However, there were no significant differences in HRs among any of the mask configurations at any given workload.

Figure 11 shows the PIE scores reported by the subjects during the testing of MCU-2/P (5 configurations) and M-17 masks at 8 incremental workloads. Overall, each mask configuration showed a progressive increase in PIE scores as a result of exposure to incremental workloads. MCU-1F and M-17 showed significantly higher PIE scores compared to the MCU-1F-ABA and MCU-ABB-2F at any given workload. Among the MCU-1F and M-17 masks these PIE scores represented sensations that ranged from "noticeable but not difficult" at the low workloads, to "slightly difficult" and "moderately difficult" at the high workloads. On the other hand, among the MCU-1F-ABA and MCU-ABB-2F masks the reports ranged from "not noticeable" at the low workloads, to "noticeable but not difficult" at the high workloads.

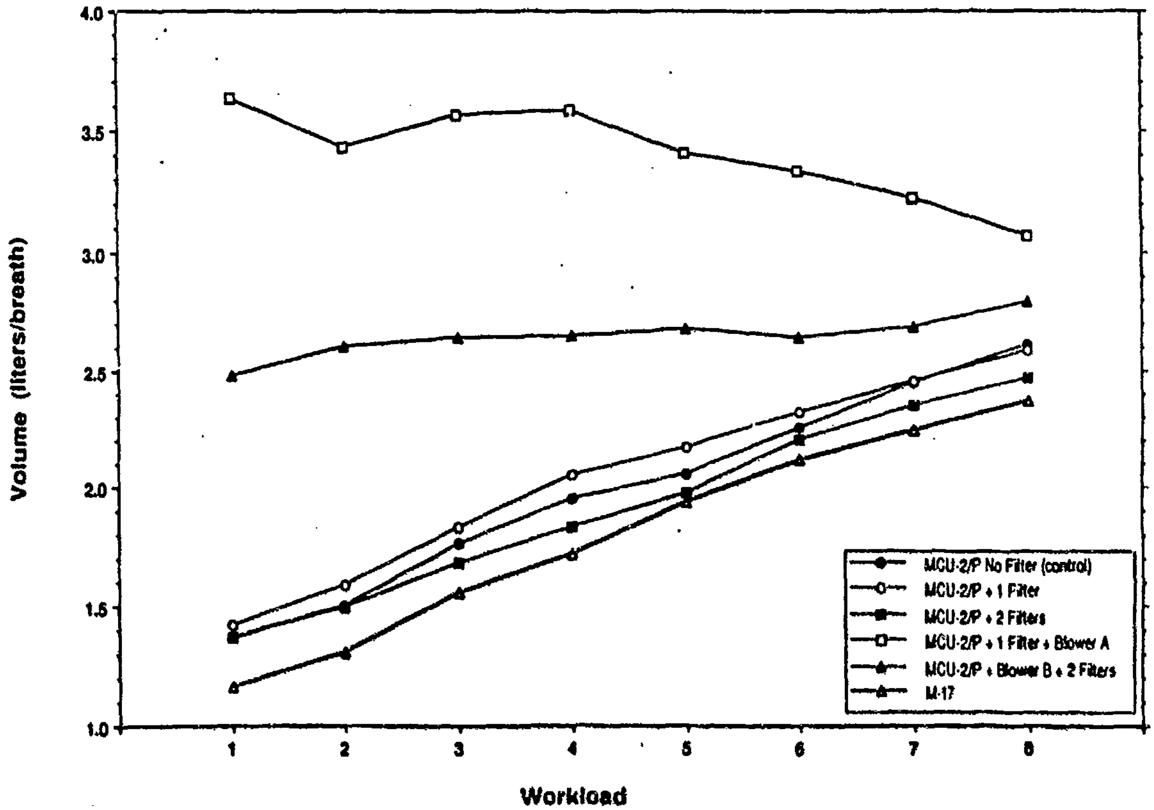

Figure 8. Tidal volumes (V_T) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

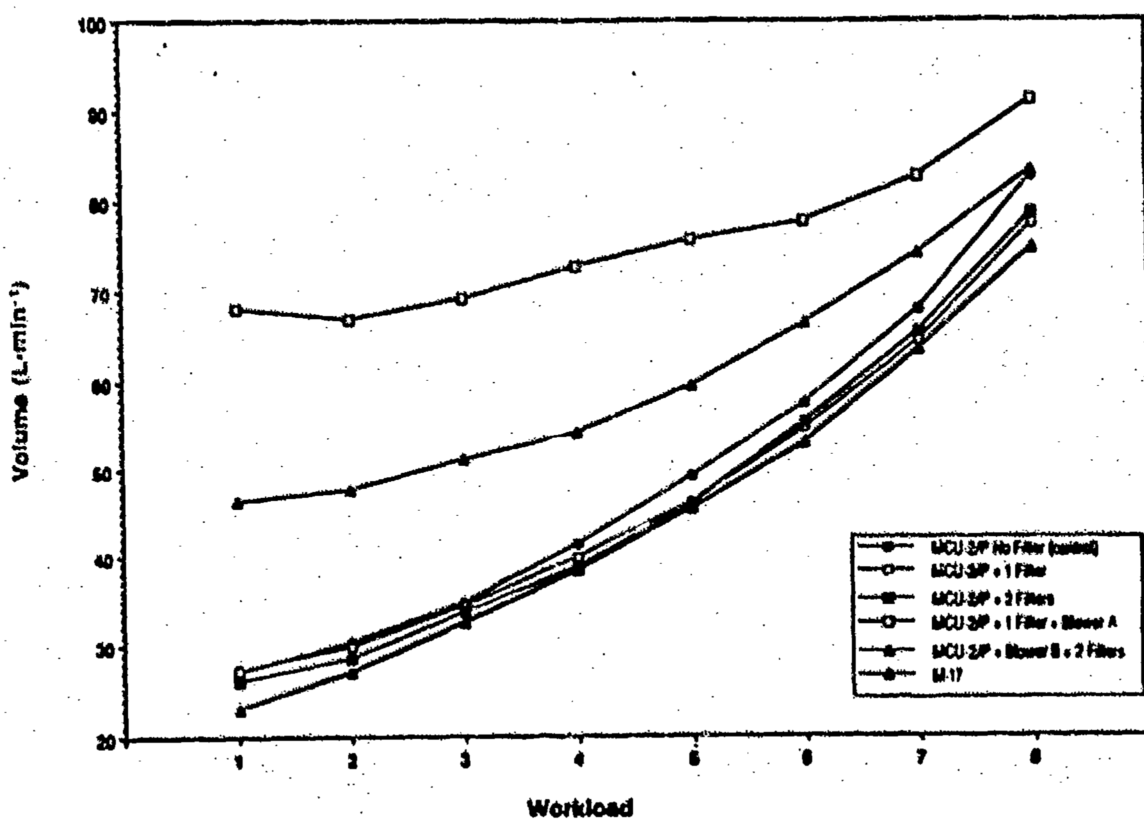

Figure 9. Ventilatory minute volumes (V_E) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

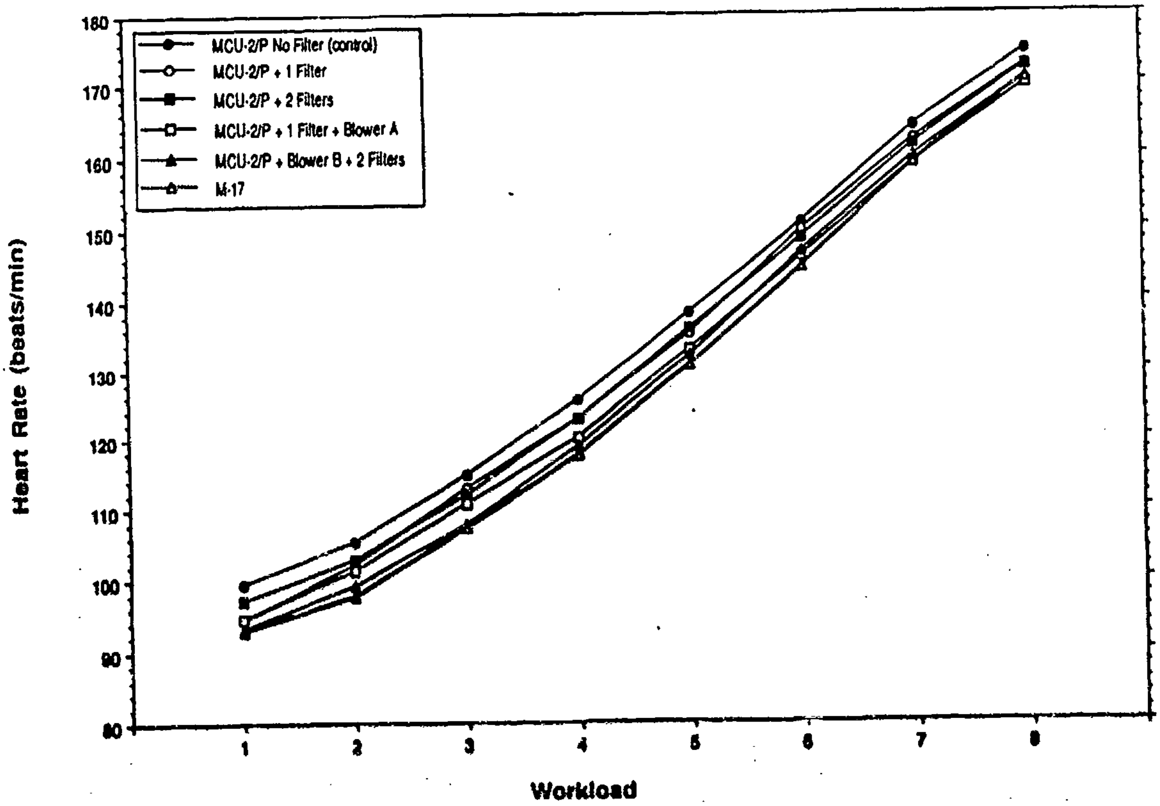

Figure 10. Heart rates (HR) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

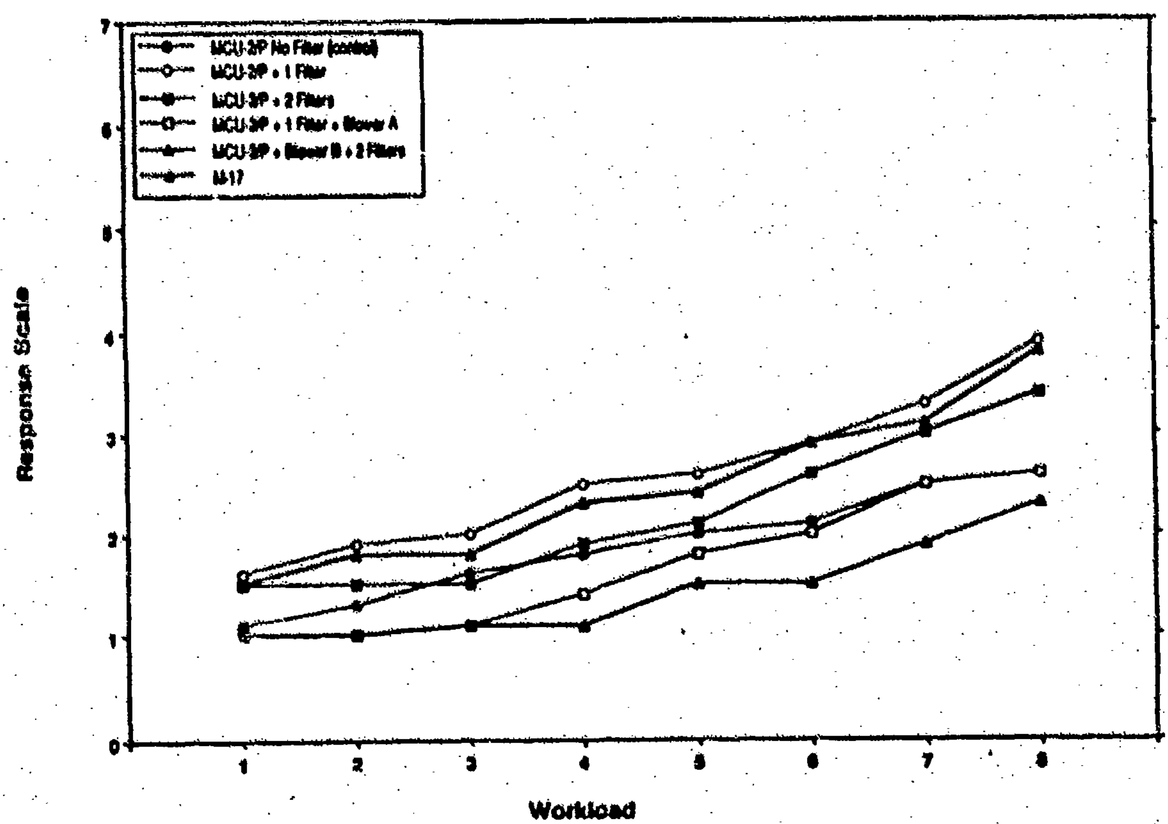

Figure 11. Perceived inspiratory effort (PIE) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

Figure 12 shows the PEE scores reported by the subjects during the testing of MCU-2/P (5 configurations) and M-17 masks at 8 incremental workloads. Overall, each mask configuration showed a progressive increase in PEE scores during exposure to incremental workloads. The highest PEE scores were observed with the MCU-1F, while the lowest corresponded to the MCU-ABB-2F. The PEE scores for the MCU-1F represented sensations that ranged from "not noticeable" at the low and moderate workloads to "slightly difficult" at the high workloads. On the other hand, the MCU-ABB-2F produced sensations that ranged from "not noticeable" at the low workloads to "noticeable but not difficult" at the moderate and high workloads. There were several other significant differences in PEE scores among the MCU-0F (control), MCU-2F, MCU-1F-ABA, and M-17; however, due to the nature of the scoring scale such differences had no practical implications.

Figure 13 shows the OBD scores reported by the subjects during the testing of MCU-2/P (5 configurations) and M-17 masks at 8 incremental workloads. Each mask configuration showed a progressive increase in OBD scores with exposure to incremental workloads. Overall, the highest OBD scores were observed with the MCU-1F, MCU-2F, and M-17, while the lowest scores corresponded to the MCU-ABB-2F and MCU-1F-ABA. The highest OBD scores represented sensations that ranged from "no discomfort" at the low workloads, and "slight discomfort" at the moderate workloads, to "moderate discomfort" at the high workloads. The lowest OBD scores ranged from "no discomfort" at the low and moderate workloads, to "slight discomfort" at the high workloads.

DISCUSSION

To assess the physiological consequences of wearing a respiratory protective mask, one must first consider the relationship between the magnitude of the IMCP and the magnitude of the additional ventilatory work (inspiratory muscle activity) required to increase the intrapleural pressure in order to overcome such an inspiratory load. Unfortunately, due to the nature of our experimental design we were not able to determine individual metabolic rates during the testing of each mask configuration.

The results indicated that the MCU-1F and M-17 masks can certainly impose high levels of external breathing resistance when the users are required to perform high physical workloads (> 60% of $Vo_{2\,MAX}$). Furthermore, these results strongly supported our previous suggestion that the mask cavity pressure characteristics of the MCU-2/P CD mask in its 1-filter operational configuration are essentially the same as those of the M-17 mask. In addition, we observed that the use of both masks resulted in similar PIAFs and similar reports of FIE and OBD scores. Therefore, it is reasonable to expect that any decrements in work performance resulting from the use of the MCU-2/P mask should be similar to those previously reported with the use of the M-17 mask.

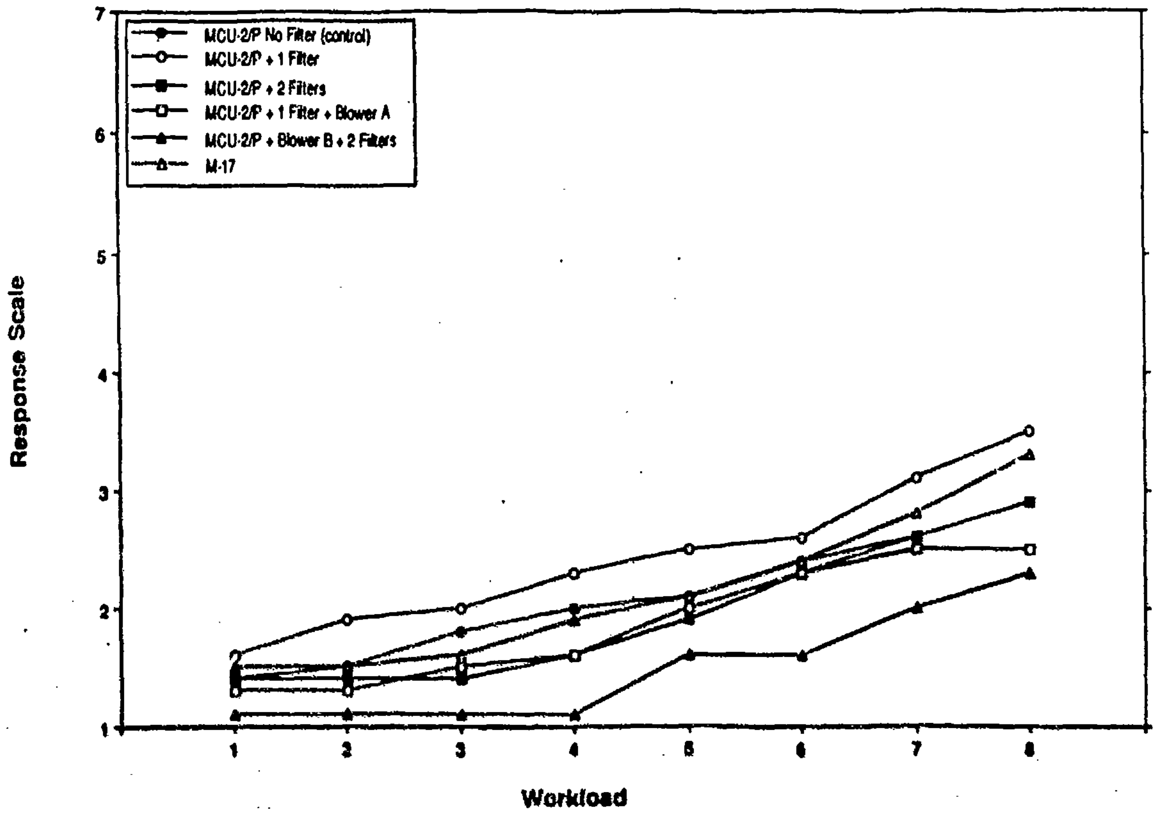

Figure 12. Perceived expiratory effort (PEE) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

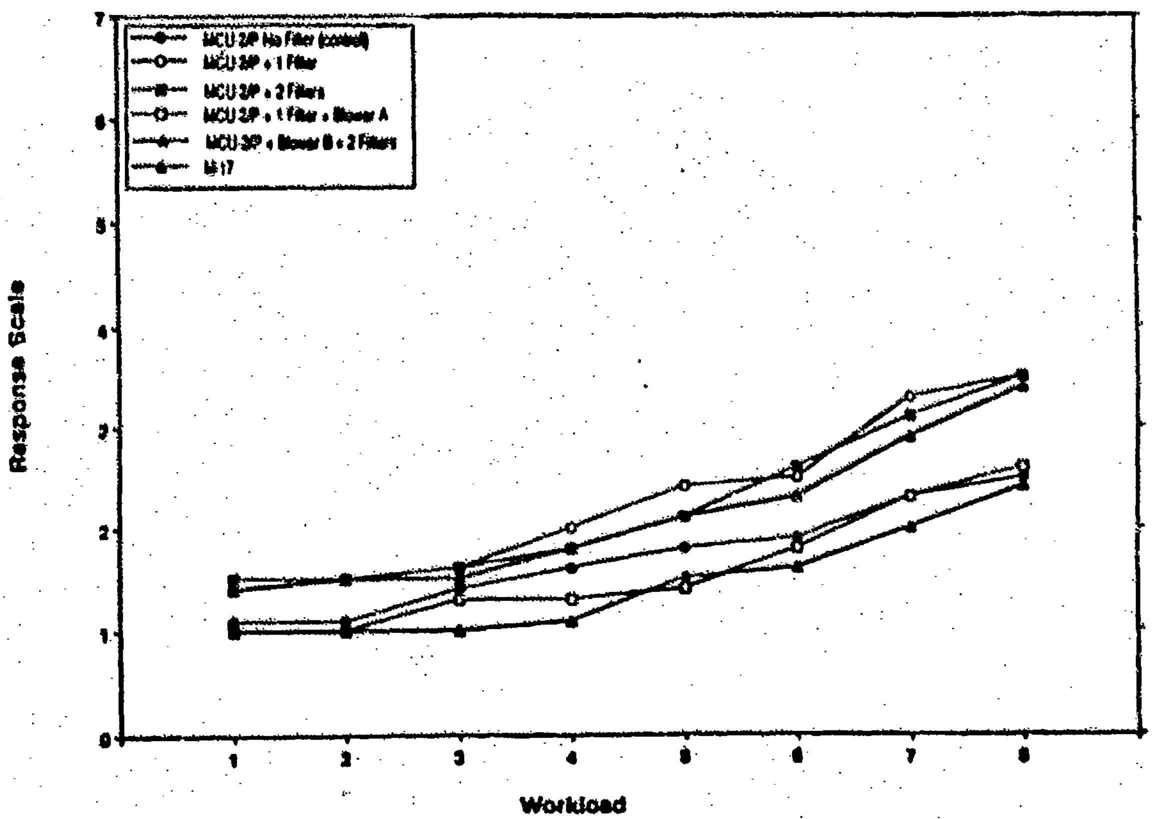

Figure 13. Overall breathing discomfort (OBD) during physical exercise (8 incremental workloads) wearing MCU-2/P (5 configurations) and M-17 CD masks.

The use of either ABA or ABB proved to be more effective in reducing the magnitude of IMCP than the 2-filter mask configuration during exposure to low workloads (26% to 34% of $Vo_{2\,MAX}$) and moderate workloads (42% to 50% of $Vo_{2\,MAX}$). Nevertheless, at high workloads (60% to 69% of $Vo_{2\,MAX}$) there were no differences in IMCP between any of these mask configurations. Furthermore, at the highest workload (77% of $Vo_{2\,MAX}$) ABA could no longer maintain a lower IMCP compared to the 1-filter mask configuration. However, ABB and the 2-filter mask configuration were both equally effective in maintaining a significantly lower IMCP. These results suggest that ABB offered the best overall method to reduce the magnitude of IMCP associated with the use of the MCU-2/P mask at any given workload (26% to 77% of $Vo_{2\,MAX}$). Results also suggest that ABA should not be used when individuals are required to perform high workloads (>69% of $Vo_{2\,MAX}$) because it does not provide any improvement over the standard MCU-2/P CD mask. The use of a second C2 filter canister attached (in parallel) to the MCU-2/P mask also represented an effective method to reduce the magnitude of IMCP at any given workload. The use of an MCU-2/P mask with two C2 filter canisters is a less expensive, more practical, and highly reliable approach. It only requires the removal of the voicemitter located on the right side of the facepiece, the insertion of an inlet valve assembly, and the installation of a filter canister.

With the exception of the MCU-1F-ABA and MCU-ABB-2F we expected to observe almost identical EMCP values for all of the other mask configurations. To our surprise, the results showed significant differences in EMCP between MCU-0F, MCU-1F, MCU-2F, and M-17. This was unexpected because the exhalation valve assemblies in each of these masks were identical. Although these statistical differences have no practical implications (physiologically speaking), a possible explanation for their occurrence may be related to the decrements in expiratory time which have been observed as a result of exposure to external inspiratory resistance. Differences in inspiratory resistance may have resulted in varied reductions in expiratory times, which in turn led to different peak expiratory flows that finally produced different EMCPs. However, this is pure speculation because we did not measure expiratory times during the experiments.

It has been reported that PIAF is reduced to a greater extent when external resistance to breathing is limited to the inspiratory phase (13). In our study, all of the mask configurations contained low-resistance expiratory valve assemblies. Therefore, external resistance to breathing was essentially limited to the inspiratory side. At any given workload, masks that imposed higher external inspiratory resistance (MCU-1F and M-17) showed lower PIAFs than those masks (MCU-0F and MCU-2F) which imposed lower inspiratory resistance. At low workloads (26% to 34% of $Vo_{2\,MAX}$) the MCU-1F-ABA and MCU-ABB-2F imposed lower inspiratory resistance than the MCU-0F (control) and showed higher PIAFs. On the other hand, at moderate workloads (42% to 50% of $Vo_{2\,MAX}$) and high workloads (60% to 77% of $Vo_{2\,MAX}$), the MCU-1F-ABA and MCU-ABB-2F imposed higher inspiratory resistance than the MCU-0F (control) and showed lower PIAFs. Although ABB provided higher PIAFs compared to ABA, it was able to maintain lower IMCPs at the highest workload (77% of $Vo_{2\,MAX}$). The reason for this difference is that ABA (Fig. 1g) was directly attached to the inlet opening of the C2 filter canister, and, at the high workload, this blower was not able to keep up with the increased individual ventilatory requirements. Under these conditions, the increased PIAFs had to overcome the resistance imposed by the blower, the filter canister, and the inhalation valve assembly. On the other hand, ABB (Fig. 1h) utilized two C2 filter canisters (attached in parallel to each side of the blower) that imposed lower inspiratory resistance during exposure to high ventilatory flow rates associated with high workloads. Under these conditions, the increased PIAFs were handled more efficiently due to the existence of two inlet openings (and two C2 filter canisters) instead of one.

Each mask configuration showed a direct relationship between RRs and workload intensity. There were also several significant differences in RRs between mask configurations at various workloads; however, the physiological relevance of any of these statistical differences was negligible. Even though we expected to observe an indirect relationship between RR and IMCP at any given workload (5,7,11), it is evident that the workload-effects shadowed the magnitude and significance of the mask-effects.

Overall, the MCU-1F-ABA and MCU-ABB-2F masks showed the highest V_{Ts} at any given workload. However, these V_{Ts} do not represent the actual breath-by-breath ventilatory requirements of our subjects, but rather the total volume of air supplied by each blower (ABA & ABB) in the breathing cycle. The almost flat V_T response-trend produced by the MCU-ABB-2F demonstrates the efficiency of this blower to keep up with the progressively increasing individual ventilatory requirements throughout the whole range of workloads (26% to 77% of $VO_{2\,MAX}$). On the other hand, the decreasing V_T response-trend produced by the MCU-1F-ABA represents the comparatively lower efficiency of this blower in response to the increased individual ventilatory needs at the high workloads. Even though there were several significant differences in V_T between some of the other mask configurations, we did not observe a clearly defined relationship between V_T and IMCP.

Zechman et al. concluded that the net result of imposed external breathing resistance is a reduced V_E (13). In our experiments, we observed a direct relationship between V_E and workload intensity among each of the mask configurations. The MCU-1F-ABA and MCU-ABB-2F masks showed the highest V_{Es} at any given workload. However, these V_{Es} do not represent individual ventilatory minute volumes, but rather the total volume of air supplied by each blower (ABA & ABB) during breathing. Although there were significant differences among some of the other mask configurations, it was not possible to establish a clearly defined relationship between V_E and IMCP.

According to Myhre, during an average 8-hour shift, trained workers show the tendency to select a physical workload that approximates 45% of their $VO_{2\,MAX}$ with a corresponding V_E of approximately 35-45 L•min^{-1} (9). This observation can have important implications for military operations where personnel are required to perform physical work while wearing CD masks. In our study, exposures to physical workloads ranging from 42% to 50% of the subject's $VO_{2\,MAX}$ (V_{Es} ranging from 38 to 46 L•min) while wearing the MCU-1F and M-17 masks resulted in IMCPs ranging from 2.8 to 3.5 inH_2O (7.1 to 8.9 cmH_2O). Individual exposure to IMCPs of this magnitude can result in decreased tolerance to sustained physical work. However, wearing the MCU-2F at the same workloads resulted in IMCPs of about 1.6 to 2.0 inH_2O (4.1 to 5.1 cmH_2O), while the use of MCU-1F-ABA and MCU-ABB-2F produced IMCPs of about 0.5 to 1.2 inH_2O (1.3 to 3.0 cmH_2O).

HRs showed a direct relationship with workload intensity, but failed to show any relationship with IMCP. This finding is similar to the results of our previous studies, and it may reflect the predominance of workload-effects over mask-effects.

Killian et al. reported that the threshold value for detection of inspiratory resistance is about 0.14 $inH_2O{\bullet}L{\bullet}sec^{-1}$ (0.36 $cmH_2O{\bullet}L{\bullet}sec^{-1}$) during moderate workload (6). In our study, the threshold for detection of inspiratory resistance among users of the MCU-1F and M-17 masks (highest inspiratory resistance) was about 1.8 $inH_2O{\bullet}L{\bullet}sec^{-1}$ (4.6 $cmH_2O{\bullet}L{\bullet}sec^{-1}$). On the other hand, the threshold for the MCU-1F-ABA and MCU-ABB-2F (lowest inspiratory resistance) was about 0.64 $inH_2O{\bullet}L{\bullet}sec^{-1}$ (1.6 $cmH_2O{\bullet}L{\bullet}sec^{-1}$). Love et al. reported that relatively easy physical work (Vo_2 = 1.6 $LO_2{\bullet}min^{-1}$) can be performed without complaint when breathing against an inspiratory resistance of 4 inH_2O (10 cmH_2O - measured at a PIAF of 100 $L{\bullet}min^{-1}$) (8). In our study, individual exposures to moderate workload 4 (Vo_2 = 1.65 $LO_2{\bullet}min^{-1}$) showed IMCPs that ranged from 0.5 to 2.9 inH_2O (1.3 to 7.4 cmH_2O) among the various mask configurations, with corresponding PIAFs ranging from 90 to 97 $L{\bullet}min^{-1}$. Under these conditions, our subjects reported PIE scores consistent with either "not noticeable" or with "noticeable but not difficult" inspiratory effort sensations. In addition, OBD scores indicated overall breathing sensations that ranged from "no discomfort" to "slight discomfort." Nevertheless, Bennet et al. reported that neither breathing pressure, ventilatory volume, nor flow alone is sufficient for a normal man to detect the sensation of external breathing resistance (1).

According to Bentley et al., when external resistance to breathing is limited to the inspiratory phase, 90% of the male population will not experience respiratory discomfort until the MCPS exceeds 6.7 inH_2O (17 cmH_2O) (2). Our subjects reported OBD scores that ranged from "no discomfort" to "moderate discomfort" at MCPSs ranging from 2.6 to 6.5 inH_2O, while wearing the MCU-1F mask. Myhre reported that an MCPS of 7.2 inH_2O (18 cmH_2O) represents a near maximal level for tolerance to breathing resistance when an individual is performing 10 min of work at 80% of $Vo_{2\,MAX}$ (10). In our study, individual exposures to the highest workload (77% of $Vo_{2\,MAX}$) resulted in MCPSs ranging from 4.4 to 8.2 inH_2O (11.2 to 20.1 cmH_2O). Under these conditions, individual reports of PIE scores ranged from "noticeable but not difficult" to "moderately difficult." Similarly, individual reports on OBD scores were consistent with subjective sensations of "slight discomfort" to "moderate discomfort." Myhre also reported that during exposure to high workload (80% of $Vo_{2\,MAX}$) an MCPS of 12 inH_2O (30 cmH_2O) imposes an intolerable feeling of suffocation which may only be tolerated for a minute or two in an emergency situation.

Zechman et al. reported that reductions in RR, increases in V_T, and decreases in V_E observed during resistive breathing are primarily the result of external resistance to exhalation (13). However, other investigators have reported similar effects when external resistance was imposed on either inhalation or exhalation (3,4,12). Furthermore, the degree to which work performance is compromised by breathing resistance is also influenced by both the resulting changes in alveolar gas exchange (O_2 and CO_2) and the individual subjective responses to stress (10). Therefore, when considering the selection of tolerance limits for resistance breathing among working individuals, it is important to keep in mind that the selection of threshold values for the initial detection, initial discomfort, and maximal tolerable level of breathing resistance vary markedly.

One important recommendation for future research concerns the development and evaluation of training protocols to facilitate and improve individual tolerance to imposed external breathing resistance. Candidate training protocols could involve different combinations of physical workloads and external inspiratory loads: 1) low physical workload and low inspiratory resistance, 2) low workload and high resistance, 3) high workload and low resistance, or 4) high workload and high resistance.

We should also attempt to identify physiological and/or psychological variables that could be used as screening indicators to predict individual tolerance to breathing resistance. A breathing resistance challenge-test could also be developed to provide a quick assessment of individual tolerance to external respiratory loads. Based on the results of this test, recommendations could be made with respect to the type of training required by a given individual.

We should also investigate other methods to counteract external inspiratory resistance associated with the use of the MCU-2/P CD mask. These could include: 1) testing of modified C2 filter canisters (prototypes are available), 2) development and testing of replacement candidates for the C2 canister, and 3) evaluation of portable blowers capable of handling the ventilatory needs of military personnel required to perform physical tasks that involve a wide spectrum of workloads. Such a blower should have the following general characteristics: light weight, small size, easy to clean and decontaminate, sturdy for rough handling, capable of sustained continuous operation, prevent excessive heat generation, reasonably quiet operation, and powered by small lightweight batteries. The use of rechargeable batteries creates a logistical problem since it requires a recharging unit and access to a power source in order to recharge the batteries. A partial solution to this problem could be the utilization of a solar-powered battery charger. A different approach could be the use of a solar-powered blower with a rechargeable backup battery (for operation during overcast conditions). Unfortunately, these expensive solar technologies are still under development and require extensive testing and validation before we can consider them for military applications.

In addition, it is necessary to conduct more research on the effects of individual exposure to combined operational stresses, which include, but are not limited to: 1) use of CD protective clothing (including mask and hood), 2) exposure to environmental heat stress, 3) exposure to physical workload of short- and long-term duration, 4) sleep deprivation and fatigue, 5) low caloric intake and dehydration, and 6) exposure to combat scenarios (including chemical warfare).

Any further human studies should include the measurement and/or calculation of several additional experimental variables: 1) average inspiratory flow rate (minute volume divided by the product of respiratory rate and average inspiratory time), 2) total external respiratory power (product of RR and the sum of external inspiratory and expiratory work per breath), 3) external inspiratory work (integral over inspiration of the instantaneous product of PIAF and IMCP), 4) external expiratory work (integral over expiration of the instantaneous product of PEAF and EMCP), 5) respiratory timing variables (breathing cycle time, inspiratory and expiratory times, inspiratory-expiratory time ratio), 6) oxygen consumption, and 7) end-tidal alveolar Po_2 and Pco_2.

CONCLUSIONS

There were no significant differences in the magnitude of external inspiratory resistance imposed by the MCU-1F and M-17 CD masks. Exposure to high physical workloads while wearing these masks resulted in high inspiratory resistive loads which can be expected to decrease individual tolerance to sustained physical work.

The use of either ABB (MCU-ABB-2F) or two filters (MCU-2F) attached directly to the mask were effective methods to reduce the magnitude of inspiratory resistance. The use of ABA was effective at workloads ranging from 26% to 69% of $Vo_{2\,MAX}$. However, at a higher workload (77% of $Vo_{2\,MAX}$) this mask configuration showed the same magnitude of inspiratory resistance as the standard MCU-2/P (1 filter) and M-17 masks.

The use of a second C2 filter canister attached in parallel to the MCU-2/P CD mask represents the most feasible (logistically, economically, technically) short-term approach to deal with the problem of external inspiratory resistance associated with this mask. On the other hand, if logistics, cost, and technological considerations are not an issue, then the best countermeasure to this problem is the use of a powered blower to provide assisted ventilation. In our study, ABB proved to be the best overall method to reduce the magnitude of IMCP associated with the use of the MCU-2/P mask at any given workload (26% to 77% of $Vo_{2\,MAX}$). However, the ideal solution to this problem is to develop a replacement for the C2 filter canister capable of maintaining low external inspiratory resistance under a wide range of individual ventilatory rates.

Although each mask configuration showed a specific IMCP response pattern, we did not observe a clear relationship between the magnitude of IMCP and the cardiorespiratory responses measured during the experiments. We suggested that workload intensity had a comparatively greater physiological impact on RRs, V_{Ts}, V_{Es}, and HRs than the magnitude of inspiratory resistance which characterized each mask.

Our recommendations for future research included among others: 1) development and evaluation of training protocols to improve individual tolerance to resistive breathing, 2) identification of physiological and psychological variables that can be used as screening tools to predict individual tolerance to resistive breathing, 3) evaluation of technological countermeasures including modified C2 filter canisters, development of replacement canisters, and testing of candidate blowers, 4) assessment of the effects of individual exposure to combined operational stresses, and 5) inclusion of additional experimental measurements in future human studies.

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APPENDIX
NUMERICAL SCALES

Perceived Inspiratory Effort Scale

Indicate the sensation that better describes your INSPIRATORY EFFORT at this moment:

1) NOT NOTICEABLE
2) NOTICEABLE BUT NOT DIFFICULT
3) SLIGHTLY DIFFICULT
4) MODERATELY DIFFICULT
5) VERY DIFFICULT
6) EXTREMELY DIFFICULT
7) INTOLERABLE

Perceived Expiratory Effort Scale

Indicate the sensation that better describes your EXPIRATORY EFFORT at this moment:

1) NOT NOTICEABLE

2) NOTICEABLE BUT NOT DIFFICULT

3) SLIGHTLY DIFFICULT

4) MODERATELY DIFFICULT

5) VERY DIFFICULT

6) EXTREMELY DIFFICULT

7) INTOLERABLE

Overall Breathing Discomfort Scale

Indicate the statement that describes your perception of <u>OVERALL BREATHING DISCOMFORT</u> at this moment:

1) NO DISCOMFORT
2) SLIGHT DISCOMFORT
3) MODERATE DISCOMFORT
4) MODERATE - HIGH DISCOMFORT
5) HIGH DISCOMFORT
6) EXTREMELY HIGH DISCOMFORT
7) INTOLERABLE DISCOMFORT